Coupled Dynamics of the Wave-Atmospheric Boundary Layer at Strong Winds

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LONG-TERM GOALS

The main goal of the proposed research is to study theoretically the role of the breaking wind waves and the sea spray, generated by them, under strongly forced situations in the airflow dynamics in particular in energy, momentum, heat and moisture transfers through the sea surface. Through this to increase the knowledge of the air-sea interaction and to apply this knowledge for developing improved, physics-based parameterizations of the fluxes (momentum, energy, heat and moisture) in the wave-coupled atmospheric boundary layer. The proposed study is essential to quantify the wave breaking effects on surface transfers, especially in the case of strong winds, where the sea spray generated by breaking waves is believed to play the dominant role in the airflow dynamics. The improved surface forcing (parameterizations of fluxes) is aimed at improvement of the performance of the high-resolution wave and coupled atmosphere-ocean models. The principle innovation of this study is that the airflow and wind waves are considered as a self-consistent interacting coupled system, where the properties of the sea surface (shape of the wave spectrum, wave breaking statistics, etc.) and turbulent characteristics of the atmospheric wave boundary layer are interrelated with each other.

OBJECTIVES

The effect is devided into 4 Tasks.

Task 1. Effect of wind waves and swell on the surface fluxes in the range of wind speeds from calm to very strong when the airflow separation from breaking wave crests dominates the aerodynamic surface roughness.

Objectives Task 1. Development of a generalized model relating the aerodynamic roughness and the surface fluxes to the statistical properties of the sea surface, which can be uniformly adopted in the Marine Atmospheric Boundary Layer (MABL) model for any sea state (developed and developing waves, swell and mixed seas) and wind (from calm to hurricane) conditions. To study the effect of the airflow separation from breaking waves on the form drag of the sea surface (aerodynamic roughness)

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at high wind conditions. To study the impact of the airflow separation on the near surface turbulence and turbulent momentum flux and implementation of results into the existing Wind-Over-Waves Coupling (WOWC) model. To combine the existing drag-swell (SWELL) and extended WOWC models in one unified model tool describing the sea surface and the near surface turbulent fluxes in a wide range of sea state and wind conditions.

Task 2. Development of a model of the spume droplets production.

Objectives Task 2. Development of a theoretical model of the spume droplets generation, which relates the rate of the spume droplets production and distribution of droplets over size to the wave breaking statistics, sea state conditions and the wind speed. To compare the model results with existing and new High-Resolution Wave-Air-Sea Interaction DRI experimental data.

Task 3. Investigation of the impact of sea droplets on the structure of the MABL and the exchange processes at the sea surface at strong wind conditions.

Objectives Task 3. Development of a MABL model coupled with waves that is valid in a wide range of the wind speed conditions, up to the wind of a hurricane force. To investigate the effect of sea droplets on the atmospheric turbulence, turbulent fluxes, wind profile through their impact on the buoyancy force and the spray stress. To investigate how the sea spume droplets and the airflow separation are tied together in setting of momentum, heat and moisture fluxes at the sea surface. Establishing new parameterizations of the sea surface transfer coefficients, and the parameters of the lower atmosphere like sea droplets concentration aiming at use and improvement of the wave/atmospheric/upper-ocean modeling including hazardous wind conditions.

Task 4. Testing of the model development on the dedicated DRI experiments and application of the model approach for the experimental data analysis.

Objectives Task 4. Application of the WOWC, SWELL, MABL, newly developed WOWC-SWELL and MABL-WOWC models for the interpretation of the High-Resolution Wave-Air-Sea Interaction DRI experiments.

APPROACH

The study is based on the Wind-Over-Waves Coupling theory/model developed by the offerors in the last decade. WOWC is a modern theory/model of microscale air-sea interaction, which allows relating the sea drag (surface stress) directly to the properties of wind waves and peculiarities of their interaction with the wind (Makin, 1998, 2005; Makin et al. 1995; Makin and Kudryavtsev, 1999, 2002, 2003; Kudryavtsev et al., 1999; Kudryavtsev and Makin, 2001, 2002). The WOWC model is based on the conservation equation for integral momentum, which relates the friction velocity to the surface stress supported by viscous stress and the form drag. The form drag is supported by the wave-induced stress and by stress due to separation of the airflow from breaking wind waves. The theory provides a clear understanding of the physical mechanisms forming the surface stress, and an explanation on what causes the stress dependence on the wind speed, wave age, finite bottom depth, and other ocean and atmosphere parameters. Thus the research combines a theoretical/modeling approach to describe the air-sea interaction in the full range of wind speeds including extreme winds with the use of existing

and new field and laboratory data for a model validation and interpretation of the experiments. It will utilize the knowledge to be obtained in parameterizations of the sea surface exchange processes, the sea drag coefficient in the first place.

The experimental effort, which underpins the present DRI, and the theoretical analysis of its results, which is offered by the present research effort, are deeply interrelated. On one side, the experiment will provide new data to check theoretical assumptions of the model. On the other, the WOWC model directly relating the surface exchanges, momentum flux in the first place, to the properties of the sea surface and its interaction with the airflow allows a clear physical explanation how the sea surface stress is formed and regulated by the surface phenomena. Waves play in that processes the dominant role. The WOWC model was successfully applied to predict stresses in a wide variety of low to moderate wind speeds and sea-state conditions. At strong wind speeds actively breaking waves and corresponding sea spray and foam production could significantly change the exchange processes.

Focusing on investigation of the air-sea interaction at high winds the WOWC model will be extended to account for the impact of the separation on the aerodynamic roughness of the sea surface by the intensive sheltering of the sea surface by separation bubbles, and the impact of the spume droplets, generated by intensively breaking waves, on the structure of the MABL including surface exchanges.

An experiment, although is an ultimate truth, is hardly able to separate effects of the multiple influences involved in the coupled system ocean-waves-atmosphere. This can be done within the theoretical/numerical models, by switching on and off different physical mechanisms. If, for particular conditions, the experiment and the model produce identical or close results, we assume that physics included in the model is adequate for the relevant field circumstances. If, on the contrary, there are essential discrepancies between the measurement and the model, such cases will be scrutinised to find the cause.

PI Dr. Vladimir Makin (KNMI) and Co-PI Prof. Vladimir Kudryavtsev (RSHMU) are the key individuals participating in this work. They coordinate the effect, develop theoretical ideas of the research, and participate in models construction and modeling. They participate in the analysis of model results and comparison studies with experimental data.

WORK COMPLETED

Task 1 to study the effect of wind waves and swell on the surface fluxes in the range of wind speeds from calm to very strong when the airflow separation from breaking wave crests dominates the aerodynamic surface roughness with the objective to study the effect of the airflow separation from breaking waves on the form drag of the sea surface (aerodynamic roughness) at high wind conditions is completed.

Task 2 to develop a theoretical model of the spume droplets generation, which relates the rate of the spume droplets production and distribution of droplets over size to the wave breaking statistics, sea state conditions and the wind speed is completed.

Task 3 to develop a MABL model coupled with waves that is valid in a wide range of the wind speed conditions, up to the wind of a hurricane force is completed. A subtask to investigate the effect of sea droplets on the atmospheric turbulence, turbulent fluxes, wind and droplets concentration profiles through their impact on the buoyancy force and the spray stress is completed

RESULTS (achieved in the report fiscal year)

Sea spray droplets are generated at the sea surface by two main mechanisms: bursting of air bubbles at the sea surface (film and jet droplets), and by the wind tearing off the wave breaking crests (spume droplets). With the wind increasing the second mechanism dominates the generation of droplets. The rate at which spray droplets of any given size are produced at the sea surface - the sea spray generation function (SGF) - is essential for many applications. At present a number of experimentally obtained SGFs are used. However, existing empirical SGFs differ from each other by several orders of magnitude, and data at very high winds are not available. Although the empirical functions are widely used for application needs, it is appealing to build a theoretical SGF based on the physical laws. Such a function on one hand will help to understand better the physics of the spray generation, and on the other hand will provide a basis to extrapolate the function to the range of the wind speed where data are absent. An attempt to build a theoretical SGF for spume sea droplets is undertaken in the present paper. A theoretical model of the spume sea spray generation is suggested (Kudryavtsev and Makin, 2009). The model is based on arguments that most of spume droplets are generated by breaking of the equilibrium range wind waves. Spume droplets being torn from an individual breaking wave are injected into the airflow at the altitude of a breaking wave crest. The pulverization of water-foam into droplets takes place in a thin turbulent boundary layer adjacent to a breaking wave crest. It is shown that the distribution of droplets over radii is proportional to the radius to the power 2. The equilibrium range waves are strongly modulated by dominant wind waves that leads to the enhancement of their breaking, so that the production of spume droplets occurs in the vicinity of the dominant wind waves crests, where from they are injected into the airflow. Solving equation for the droplets concentration the spray generation function is obtained and compared with empirical functions. Few empirical functions were selected for the comparison and a reasonable agreement in the spectral level, integral flux and shape of the spray generation function is found. This theoretical SGF serves as a module in the MABL model.

The impact of ocean spray on dynamics of the marine atmospheric boundary layer (MABL) in the conditions of very high (hurricane) wind speeds was investigated. To that end a model of the MABL in presence of sea spume spray is suggested. A classical theory of the motion of suspended particles in a turbulent flow of incompressible fluid is applied to describe the interaction of the sea spray droplets with the airflow. The only difference with the classical formulation is that the mass concentration of droplets is considered to be not mandatory small. Thus terms containing the mass concentration are not neglected in the momentum conservation equation. The derived conservation equations for mass and momentum are valid above instantaneous water surface: between wave crests and troughs, and aloft. The impact of spume droplets on the airflow is modeled by the source term incorporated into the mass conservation equation. The model of the spume droplets production assumes that droplets being torn off from crests of breaking equilibrium wind waves are injected into the airflow at the altitude of these breaking waves. This process takes place at the crest of dominant waves. The volume source of droplets is related to the spectral density of the breaking front length, which in turn is related to the saturation spectrum of wind waves. The parameters of the mixture (droplets concentration, the mixture density, the total flux of droplet) exhibits similar features: they have maximum at the altitude corresponding the height of shortest breaking waves and rapidly attenuate with increasing height. The impact of spray on the airflow is realized via two terms entering equations for the wind profile and the drag coefficient. One term, the so-called spray stress appears in these equations because of the variation of the mixture density; the other one enters the problem via the buoyancy term by modifying the Monin-Obukhov length scale. It is shown that the main impact of droplets is provided by the

buoyancy term resulting in the significant modification of the wind velocity profile and the momentum flux: the wind speed is considerably increased and the drag coefficient exhibits saturation at the wind speed of about 40 m/s and further levels off with increasing wind speed. This is with agreement with recent experimental data acquired in hurricanes.

IMPACT/APPLICATIONS

The main innovation of the project is the development of the advanced model describing the exchange processes at the sea surface in extreme wind conditions. This covers the improved description of the sea surface and the WOWC model, and assessment of the sea spray role in the momentum flux above the sea. The project will provide new knowledge and parameterizations of the sea surface fluxes, which will be valid for the whole range of wind speeds and sea surface conditions and can be used as improved boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean-atmosphere systems, and covers all spatial and temporal scales from local high-resolution to global climate studies. Therefore, this study directly addresses social needs to improve climate variation predictions, weather forecasts and to reduce the impact of natural hazards caused by extreme wind and sea-state conditions.

RELATED PROJECTS

PhD research “Air-sea interaction and sea-state forecasts in extreme weather conditions”, 2007-2011, funded by Netherlands Organization for Scientific Research. The main goal of this research is to apply consistently new parameterizations of the sea drag to the sea state and atmosphere models with focusing at extreme weather conditions and aiming at models improved performance. Parameterizations, which will be obtained in the course of the DRI effort, are obvious candidates for the testing.

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